Case Studies on Evaluation of Liquefaction Resistance in terms of Combination of Surface Wave Exploration and Electrical Prospecting

H. NAKAZAWA
Fukken co., ltd. (*Formerly Port and Airport Research Institute*)

T. SUGANO & E. KOHAMA
Port and Airport Research Institute

SUMMARY:
The functions of airports are probably suspended when liquefaction of the ground in the airports happens due to large earthquake motion especially when their runway and taxiway pavement is significantly damaged by liquefaction-induced differential settlements. Therefore, it is important to assess liquefaction resistance of the ground beneath the runway and the taxiway. This paper describes that the supplemental method in terms of combination of surface wave exploration and electrical prospecting was able to evaluate the liquefaction resistance by the relationship between S-wave velocity and resistivity in liquefiable layer. Through investigations at sites in two airports, the liquefaction resistance of reclamation and the feature of soil improvement constructed were confirmed each other by this method.

Keywords: Liquefaction, surface wave exploration, electrical prospecting, runway, taxiway

1. INTRODUCTION

Liquefaction phenomenon has been observed as a kind of ground failure after strong earthquake and damaged various structures. In order to assess the liquefaction potential of soft ground, Standard Penetration Test, SPT have been usually performed in Japan. Results of SPT and some kinds of laboratory tests with undisturbed samples show the reliable information to assess liquefaction potential, however, this traditional method is often inappropriate because of expensive cost, limited time for operation, limited information in extensive site like airport, and unsuitable site condition. Therefore, convenient methods instead of SPT are necessary for the reasonable interpretation of liquefaction potential.

The other side, focused on the damages during and after large earthquake in airport site, it is feared that their function will be suspended when the ground in airport site is liquefied by large earthquake, because various important facilities are installed there. Especially, runway and taxiway pavement, which performances need bearing capacity and keeping allowable surface deformation after earthquake, will be damaged by differential settlements with deformation of the ground induced by liquefaction. In this case, it is thought that there is a possibility to stop the present serviceability even if the damage to runway pavement structure is locally caused by liquefaction. Therefore, the prediction of residual deformation and the plan of countermeasure against liquefaction are very important for earthquake resistant design. However, boring investigation for liquefaction potential on runway and taxiway pavement is required that its investigation in an airport site must be carried out in several hours of midnight to avoid interrupting the time of airport operation in Japan. It is not enough time to complete boring investigation including SPT and undisturbed samplings in the site, which is usually required at the depth of about 20-30 m in the airport site. Accordingly it is thought that application of physical exploration which can be completed more rapidly compared with SPT.

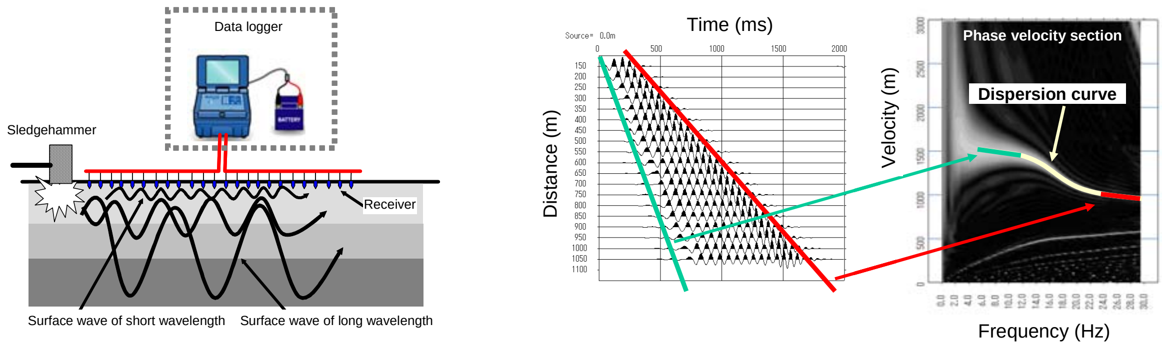
In this study, two different physical explorations, Surface Wave Method and Electrical Prospecting, were carried out along the runway in the Matsuyama Airport and the taxiway in Tokyo International Airport. As a result obtained from these two sites, it was confirmed that combining existing boring results with Surface Wave Method and Electrical Prospecting was effective as a technique for an interpolation of the existing geological information obtained from boring investigation and able to estimate the liquefaction potential considered reflecting the characteristic of the site significantly.

2. PROCEDURE OF FIELD SURVEY

2.1. Surface Wave Exploration Method (SWM)

Surface wave exploration method (SWM) is an in-situ soil investigation method. Analysing records of dispersed surface waves, distribution of shear modulus, G_o, of the subsoil can be obtained. Main steps for this method are estimating the dispersive characteristics of a site by means of acquisition and processing of seismic, further inverting the data for estimate of the subsoil properties. At last, the vertical profile of the shear wave velocity, V_s, is obtained. In order to recognize the various propagation characteristics of the seismic wave field, Common Mid-Point cross-correlation analysis of multi–channel surface wave method was applied in this study to provide more accurate phase velocity curves. This analysis could also reconstruct 2-dimensional velocity structures with high resolution (Hayashi and Suzuki, 2004).

A schematic view of SWM is shown in **Figure 2.1**. The equipment for this survey was composed of a data logger, geo-phones and sledgehammer. In this study, a survey line was determined to construct the shear wave velocity profile down to about 10-15m of the site. 24 geo-phones of 4.5 Hz resonant frequency were deployed at 1 m spacing along the survey line with receivers connected to multi-channel recording device. 10 kg sledgehammer was used as the active source placed with 1 to 2 m intervals. After the field work, the cross-correlations analysis was applied to multi-channel and multi-shot surface wave data. Based on nonlinear least squares inversion, a 2-dimensional surface wave velocity profile was reconstructed. The detailed procedure of the cross-correlations analysis is available elsewhere (The Society of Exploration Geophysicists of Japan, 2008).



(a) Schematic view of a surface wave method (b) example of dispersion curve

Figure 2.1. Outline of surface wave method

2.2. Electrical Prospecting

As an electrical prospecting, the capacitively-coupled resistivity experiment, CCR was conducted to estimate the soil types in this study. In this method, there is no necessity to install electrodes into the ground, and this advantage enables more rapid surface surveys than conventional D.C. resistivity surveys. Therefore, application of this method for investigation along long survey lines is very effective. It is noticeable it may be difficult to apply on conductive soil or in urban areas with many underground structures.

The concept of the CCR measurement is illustrated in **Figure 2.2**. At application of voltage to the conductor inside the CCR transmitter, an electric charge appears between the conductor and the ground which are separated by the insulation. The conductor and the ground act as two plates of a capacitor separated by a strong dielectric resistor. This capacitance between the conductor and the ground behaves as a path for an A.C. current flowing from the conductor to the ground. According to the same principle, it is possible to detect the A.C. voltages in the ground generated by the transmitter with a CCR receiver. In this manner the resistivity of the ground can be acquired. **Figure 2.2** also shows a photo of the five-receiver system. The receivers are connected to each other by shared dipole cables, and the transmitter is connected to the receiver array by a non-conductive rope. The transmitter/receiver array is usually portable (Yamashita et al., 2004).

The specification of this method is shown in the followings; a) Operating Range is from 3 to 100,000 Ohm-meters, b) Selectable data logging up to 2 scans/sec, c) Frequency is 16.6 kHz, output power is up to 2 Watts and output current is 0.125 mA to 16 mA on Transmitter, d) Selectable cable lengths are 1, 2.5, 5 and 10 m, especially 10 m is standard, Input impedance is more than 5 MΩ, Measured voltage accuracy is better than 3 % and Input voltage is ranged 0-2 V RMS on Receiver.

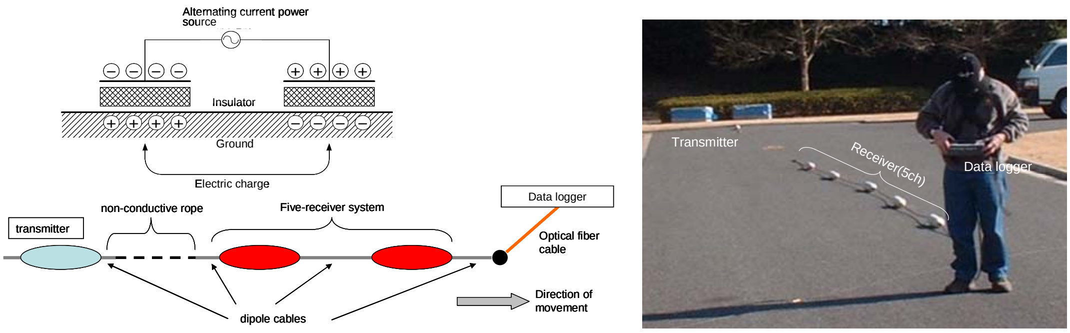


Figure 2.2. Concept of the capacitively-coupled resistivity measurement and the five-receiver system

Table 2.1 summarizes typical numbers of resistivity which is widely varied with some parameters of soil. According to this table, the value of resistivity is totally dependent on type of soils (i.e. 1 for clay, and 1000 for gravel). Using this feature, the type of the soils can be clarified based on the order of resistivity(Calamity Science Institute, 2001).

Table 2.1. Relationship between parameter of every soil type and resistivity

Low ---------	Resistivity		--------- High
~1	Ω・m		10^3~
(Clay)	(Silt)	(sand)	(Gravel)
Low ---------	Grain size		--------- High
High ---------	Degree of saturation		--------- Low
High -----	Moisture content by volume		----- Low
Low ---------	Formation resistivity		--------- High

3. SITE CONDITIONS AND RESULTS OF INVESTIGATION

In this chapter, summary of the existing geological information concluding SPT data and the results of SWM and CCR in Matsuyama Airport and Tokyo International Airport are described.

3.1. Matsuyama Airport

3.1.1. Summary of existing boring and laboratory tests data

The plan view of SWM, CCR and existing boring locations in Matsuyama Airport are shown in **Figure 3.1**. SWM and CCR were carried out on the runway pavement. In this site, there have been three times of reclamation constructions for runway extension. Coastal lines before reclamation and after each reclamation work are also shown in this figure. It is confirmed that the survey line crosses all three reclamation areas, the first through the third term construction. The typical boring log and soil profile along the survey line is shown in **Figure 3.2**. The soil profile of this site is roughly summarized as follows.

a) The survey line was 1,000 m along the runway pavement crossing the three coastal lines at any reclamation terms. The reclamation work of the first area was completed approximately 50 years ago, and the second area was done about 40 years ago. Finally, the third reclamation has been performed in the left area of the **Figure 3.1**.

b) Soil strata: The top layer, Bs1 and Bs2, consisted of gravelly to silty sand was 5-6 m thick and very loose to medium dense with 5-27 of *N*-value. The deposit of gravel with silt below Bs2 was about 20m thick and widely ranged 6-47 *N*-value, which was next to the coastal line. Soil properties in Bs1, Bs2 and Bg were partially uneven because it is supposed that three construction terms were different. The ground water level which was equivalent to 0 m of sea level (T.P.±0 m) was about GL.-4.0 m located in the Bs1 layer.

c) The Alluvial layers of As1, As2 and As3, the original marine sediments underlying Bg, were consisted of fine sand, sand with silt and silty sand, and showed the ranges of 1-13, 5-25 and 2 to 31 of *N*-values respectively.

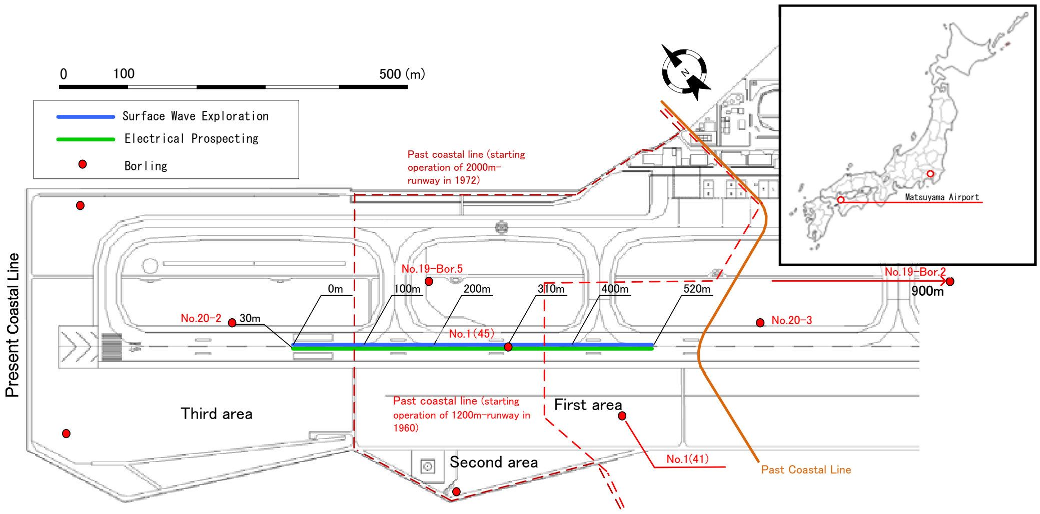


Figure 3.1. Matsuyama Airport site

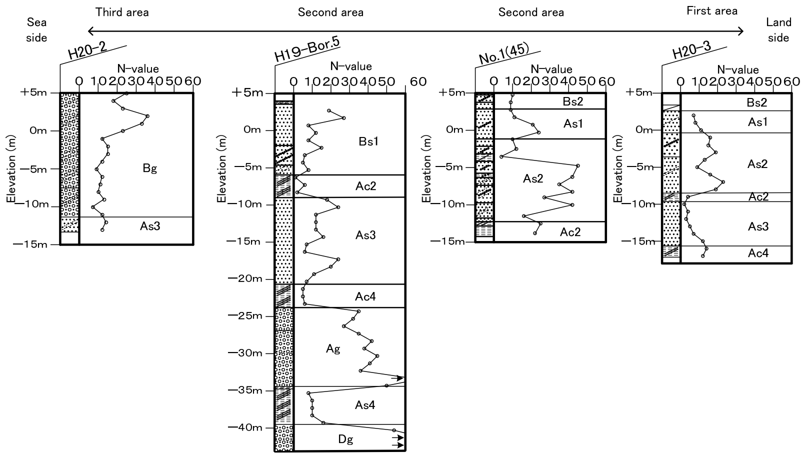


Figure 3.2. Existing boring logs along field survey line

3.1.2. Results of Surface Wave Method and Electrical Prospecting

The results of SWM and CCR are shown in **Figure 3.3**. The mesh for analysis in these figures is 2.0m in horizontal direction and 0.7, 1.5, 2.5, 4.0, 5.0, 6.0, 7.3, 8.8, 10.4 and 12.1m vertically from the surface of the asphalt pavement.

Based on the result of SWM, V_s at the top 5 m of the ground in the third area shows more than 290 m/s between 0 and 90 m from the west end of the survey line. In this area, however, low V_s distribution indicating possible liquefiable layer, can not be detected. On the other hand, continuous distribution of low V_s which shows less then 160m/s, can be observed from 90 to 520 m in the second and first areas.

Next, focusing on the resistivity map plotted by analysing CCR records, the resistivity varied from 67 to 220 Ωm is continuously distributed in shallow layer above GL-5m. On the other side, layer with resistivity less than 67 Ωm is mainly distributed below GL-5m. This layer seems discontinuous from the figure, but the CCR records may be affected by underground structures or something else, and therefore, the layer is probably continuous along entire length of the survey line. As an interpretation of the resistivity, in case of high resistivity more than 100 Ωm, the layer consists of sand and gravel remarkably and lower resistivity means that silt is remarkable in sedimentary layer, as shown in **Table.2.1**. For instance, focused on the layer below GL-5m, because As2 and Ac2 layer is almost including silt according to boring log, it seems that the boring result and CCR are nearly matched respectively though resistivity is lower compared with typical value of silt.

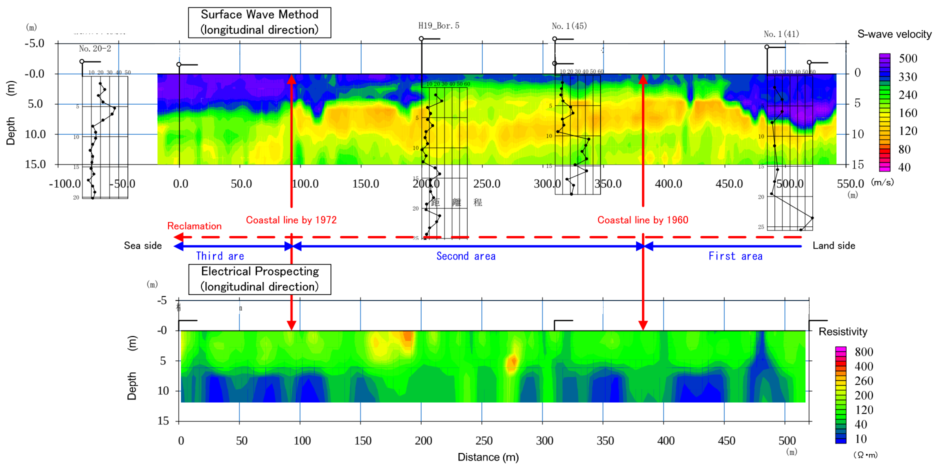


Figure 3.3. Results of Surface Wave Method and Electrical Prospecting in Matsuyama Airport

3.2. Tokyo International Airport

3.2.1. Summary of existing boring and laboratory tests data

The plan of SWM and CCR carried out along the taxiway and the existing boring points in Tokyo International Airport is shown in **Figure 3.4**. The surveyed area is reclaimed land by dredged soil. The Compaction Grouting Method, CPG, as a countermeasure against liquefaction was partially constructed in the liquefiable soil under the taxiway. As shown in **Figure 3.5**, there were twelve areas with ground improvement along 500 m of the survey line. The specifications of the improved and untreated areas and soil properties in the main stratum were as follows;

a) The reclaimed soil layers consisted of backfilling, dredged sandy and clayey soil layer and alluvial deposits are detected in order from the ground surface. The reclaimed soil layer is divided into three layers, Bs, As0 and Ac1 layers classified depending on each soil materials. The targets of the geophysical exploration in this study are Bs and As0. Bs layer includes various kinds of materials, such as asphalt, crushed stone and fine sand with silt in the pavement and gravelly sand with silt as a main geo-material below the pavement. Also, it is recognized that fragment of concrete, improvement soil, asphalt and brick splinter are composed in Bs. Moreover, *N*-value is widely distributed with 1 to more than 50. On the other side, As0 is mainly consisted of sand with silt and sand with gravel, which are poorly graded. *N*-value is distributed within the range of 6 to 43.

b) According to **Figure 3.5**, the top layer, Bs was a compacted sub-grade about 1.5m thick, and lying under the sub-grade was a fill layer at the depth of 10-15m. Lying further blow was about 7-8m-thick silty sand layer of dredged sludge, called As0. The groundwater level in Bs was averagely GL.-5.0 m equivalent to T.P.±0 m.

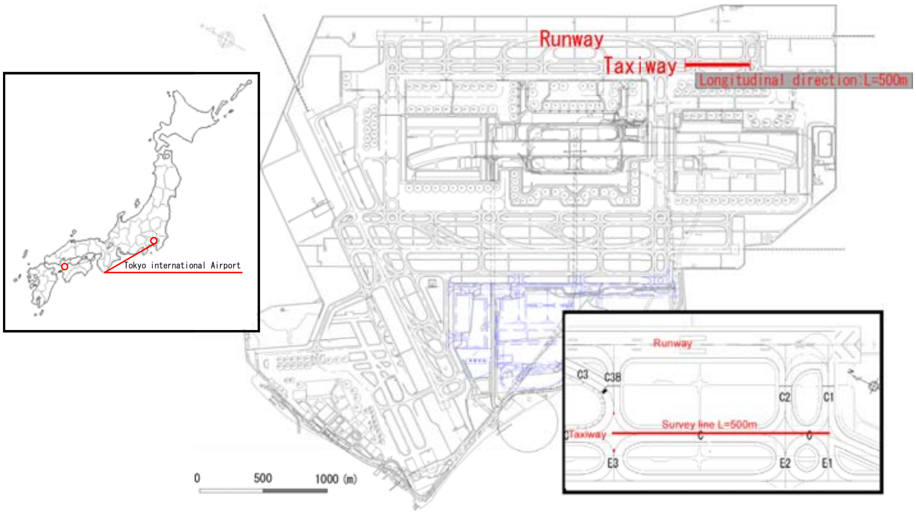


Figure 3.4. Tokyo International Airport site

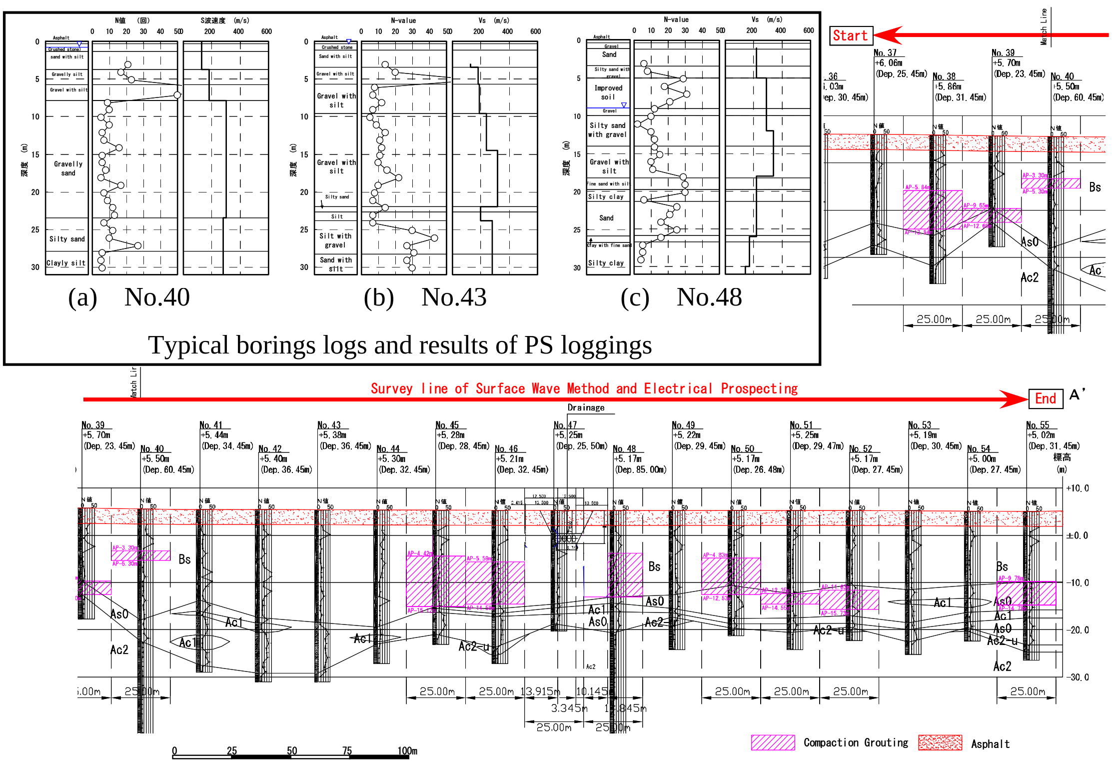


Figure 3.5. Geologic section along survey line

3.2.2. Specification of Compaction grouting

Improved areas by CPG, were recognized in **Figure 3.5**. CPG is a method of pumping grout with very low mobility of less than 5 cm slump into the ground under pressure to form grouts without vibration and shocks. As the grouts increase their volume, the surrounding ground is densified to increase its density, as illustrated in **Figure 3.6**. The range of improvement rate, α_s, is 8 to 15 %, and the grouting pattern is typically regular triangle with 1.2 to 1.7 m spacing in center-to-center (Coastal Development Institute of Technology, 2007).

a) Each CPG was applied to the liquefiable depths in Bs and As0, which was estimated from seismic response analysis. α_s was designed as 8 to15 %, and it was verified that N-values in the improved portions were significantly larger than the original N-values in both the layers.

b) According to soil investigation report, fine contents, F_c, of Bs and As0 were widely varied from 10 to 50 %, and both the layers were not homogeneous. Especially plasticity index, I_p, in Bs showed less than 37.8. The other side, liquefaction strengths, R_l, defined as cyclic undrained shear stress ratio, $\sigma_d/2\sigma_c$' at 5 % of double amplitude, *DA*, and 20 counts of cyclic numbers under isotropic condition, were investigated by tri-axial test and increased about 0.3 of pre-CPG to about 1.3 times pre-CPG's one.

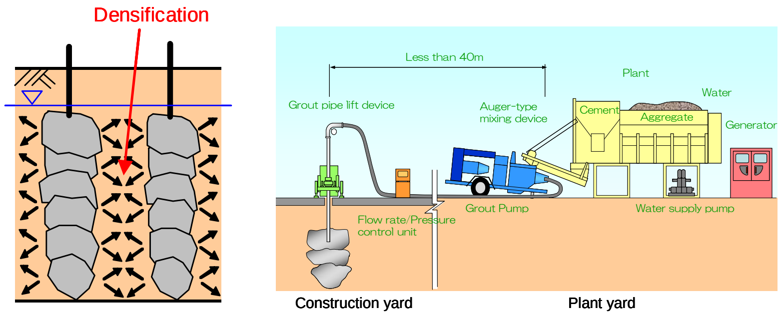


Figure 3.6. General use of compaction grouting

3.2.3. Results of Surface wave method and Electrical Prospecting

2-dimensional results of SWM and CCR are shown in **Figure 3.7**. The meshes in these figures are 2.0 m horizontally and 0.5, 1.2, 1.9, 2.6, 3.5, 4.5, 5.5, 6.6, 7.8, 9.1 and 10.4 m vertically for SWM, and 2.5 m horizontally and 0.6, 1.6, 3.2, 5.8 and 10.0m vertically from the surface of the asphalt pavement for CCR. In the 2-dimensional V_s section, data with light color in deep layer is less reliable, and therefore, the V_s structure up to approximately GL-10 m from the ground surface could be obviously estimated in this survey. In addition, the figure indicates V_s in most of the surveyed area is 200 to 300 m/s. As an exception, areas with high V_s appear around the ground surface due to asphalt pavement. And the other exception, there are the portions with larger V_s around the center of the figure. These portions are roughly corresponding to improvement by CPG, though the appearance of CPG by SWM was about 2 to 3 m shallower than the design shown in **Figure 3.5**.

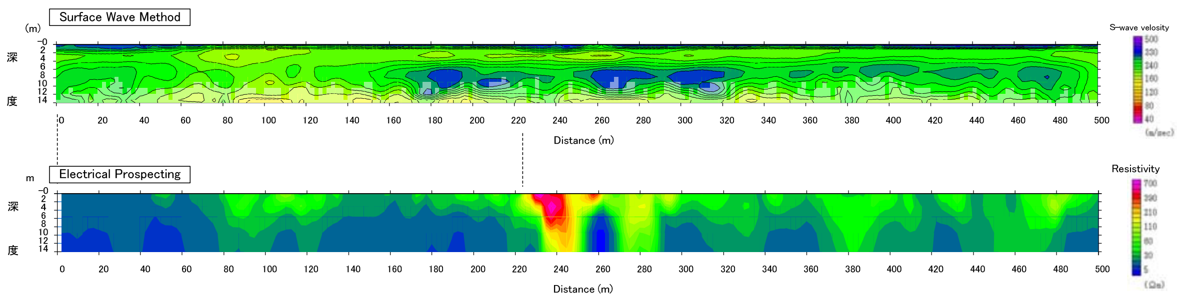


Figure 3.7. Results of Surface wave Method and Electrical Prospecting in Tokyo International Airport

Focusing on the result of CCR, it is tendency that resistivity is low all over the investigation line because of 2 mA of energizing value into the ground. In the left portion of the figure, the distance between 0 and 210 m, there seems the portion less than 20 Ωm of resistivity. On the other side, in the distance between 220 and 500 m, the higher resistivity of 30 to 100 Ωm compared with the left portion is detected wholly though the low resistivity part less than 20 Ωm partially exists. The high resistivity area observed in the distance about 240 m is corresponding to the position of the drainage trench.

4. ESTIMATION OF LIQUEFACTION RESISTANCE

4.1. Boundary Values between liquefaction and non-liquefaction

1-dimensional distributions of normalized V_s, V_{s1} and resistivity at a typical point of Matsuyama Airport is shown in **Figure 4.1**. In these figures, V_{s1} based on the below equation (4.1), which is equivalent to 98 kPa of effective confining pressure is expressed to consider confining pressure dependency on V_s. (R. D. Andrus et al., 1999)

$$V_{s1} = V_s\left(P_a/\sigma_v'\right)^{0.25} \tag{4.1}$$

where, P_a is 98 kPa as standard confining pressure, and σ_v' is effective confining pressure. In case of Matsuyama Airport, the liquefiable layers are composed of sand, fine sand and sand with gravel. The boundary values between liquefaction and non-liquefaction were assumed to be 200 m/s of V_{s1} and 50 Ωm of the resistivity for the soil type respectively. On the other side, it was judged that 250 m/s of V_{s1} and 20 Ωm of resistivity as boundary values in Tokyo International Airport.

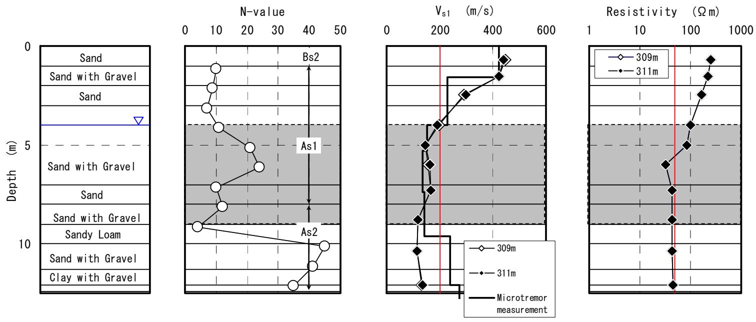


Figure 4.1. Example of distributions of S-wave velocity and resistivity

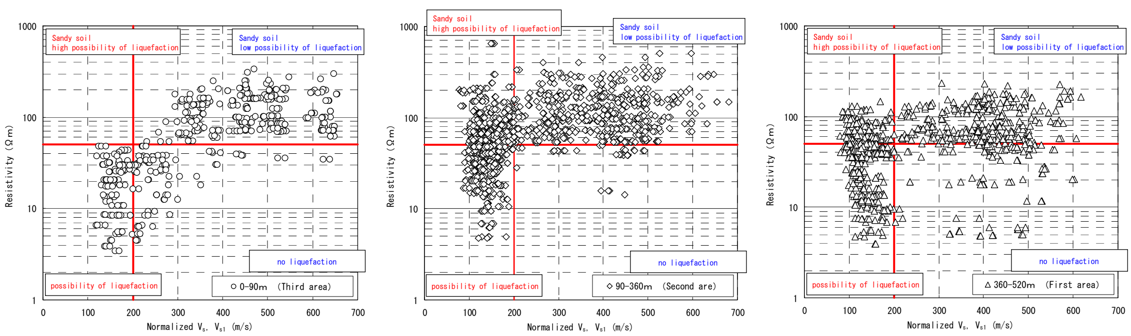
4.2. Estimation of liquefaction resistance

The relationship between V_{s1} and resistivity obtained from the results of SWM and CCR along the same investigation line in Matsuyama Airport is shown in **Figure 4.2**. All the marks in this figure are the data below underground water and separately plotted for each reclamation period. The tendencies for each reclamation construction are summarized as follows.

a) Figure 4.2(a) for the third reclamation construction indicates that the relationship between V_{s1} and resistivity seems comparatively linear. However, it seems that many marks distribute in the range of high V_{s1} and cohesive soil. Therefore, it is estimated that this area is under the condition of low possibility of liquefaction.

b) Most marks in Figure 4.2(b) for the second reclamation construction are distributed within the zone with low V_{s1} and high resistivity. Therefore, the ground in this area is under high possibility of liquefaction.

c) Figure 4.2(c) includes the results for the original coastal deposits as well as for the reclamation in the first construction. In this figure, there is an intermediate tendency between the second and the third reclamation, and a lot of plots of resistivity are distributed especially within the range of 50-100Ωm.



(a) Third reclamation (b) Second reclamation (c) First reclamation

Figure 4.2. Relationship between normalized S-wave velocity and resistivity in Matsuyama Airport

Based on **Figure 4.2**, the range for estimation of liquefaction susceptibility is divided into four blocks which means high possibility, possibility, low possibility and non-liquefaction for each blocks and these estimation applied to the section of runway pavement along the survey line in **Figure 4.3**. Additionally, this figure targets the depth of range from GL-4.0 m of underground water to GL-10 m that the estimation by physical exploration can be carried out. Focused on estimation of the second reclamation construction, it is judged as high possibility of liquefaction. Considered liquefiable soil type by CCR, this area is comparatively corresponding to the range of low V_s shown in **Figure 3.3**.

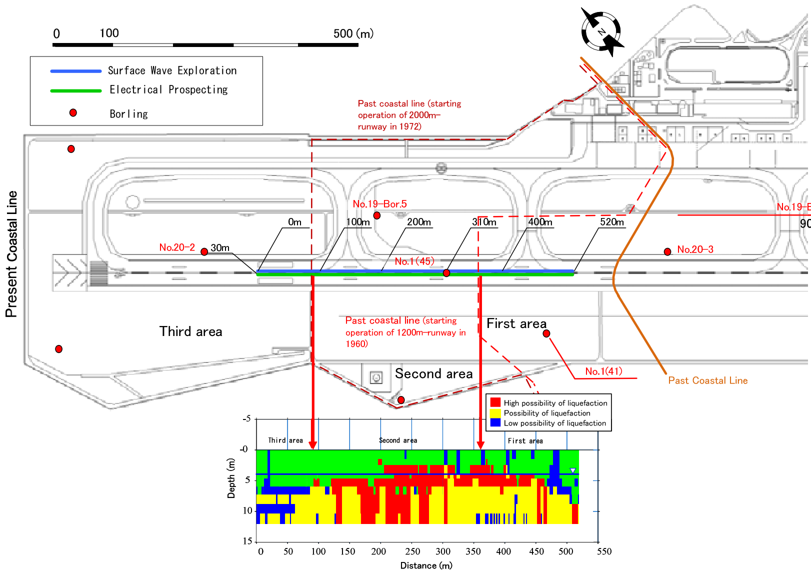


Figure 4.3. Estimation of liquefaction resistance in Matsuyama Airport

Figure 4.4 shows the estimation of liquefaction resistance in Tokyo International Airport, based on relationship between V_{s1} and resistivity in the depth from GL-5 m to GL-10 m which is equivalent to liquefiable deposit and divided into four estimation areas like as the case of Matsuyama Airport. In this figure, it is verified that the areas of 1, 4, 5, 6 and 7, in which the top of the ground improvement is shallower than GL-10 m, show low possibility of liquefaction. In the left portion of the investigation line, the unimproved soil layers are possibly liquefiable. Comparing this evaluation results with the geologic section and the boring investigation results, all the results are roughly consistent each other. It seems that there is a room of additional research to qualify the threshold of V_{s1} and resistivity because these prescribed values may be dependent on sites.

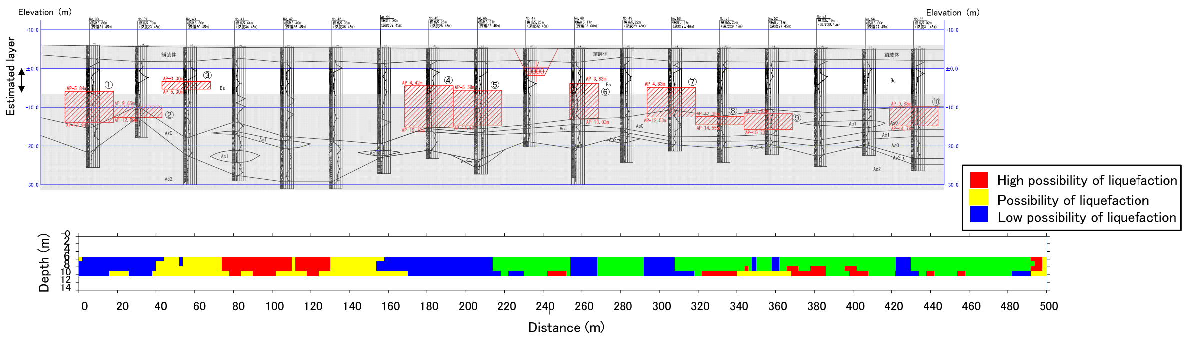


Figure 4.4. Estimation of liquefaction resistance in Tokyo International Airport

5. CONCLUSIONS

To evaluate possible damage level of airports after strong earthquake, an only usual boring investigation is insufficient, and it is important to appropriately evaluate distribution, continuousness and liquefaction resistance of liquefiable layer. Therefore, the ground beneath the runway pavement and the taxiway in two airport sites were surveyed with the boring investigations and the geophysical exploration as supplemental technique. The findings from this study are shown as follows.

a) To confirm distribution and continuousness of liquefiable layer in Matsuyama Airport, the surface wave exploration and the electrical prospecting were conducted along the runway. The features of the S-wave velocity distribution indicate that recently reclaimed soil stratum shows lower V_s, and this layer was evaluated as a liquefiable layer.
b) In Tokyo International Airport, SWM and CCR were conducted to examine the depth of soil improvement with densification method. According to the result of SWM, the effects of ground improvement could be verified as the zone with more than 300m/s of V_s. On the other hand, most of improvements showed low resistivity on the investigation line from 220 m to the end. Based on this result, using V_{s1} and resistivity, the area of the soil improvement was detected comparatively well.
c) The evaluation of liquefaction resistance in terms of combination of surface wave exploration and electrical prospecting is very effective.

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